# FACIAL COOLING DURING COLD AIR EXPOSURE

BY PETER TIKUISIS AND RANDALL J. OSCZEVSKI

A recently developed dynamic model of wind chill is applied herein for the prediction and interpretation of facial freezing times.

The United States National Weather Service and the Meteorological Service of Canada simultaneously implemented a replacement wind chill temperature (WCT) index on 1 November 2001 (available online at www.nws.noaa.gov/om/windchill/ and www.msc.ec.gc.ca/education/windchill/, respectively). The WCT index provides a prediction of the calm air temperature that would result in the same rate of steady-state heat loss as an exposure to a higher temperature with wind. The current version is based on more accurate and relevant data with respect to human tissue cooling, specifically of the face (Osczevski 2000). The evolution of this index inspired us to develop a complementary dynamic tissue-cooling model for the purpose of predicting cheek-cooling times with a particular emphasis on the onset of freezing (Tikuisis and Osczevski 2002). Such predictions are especially pertinent for flat, open regions that experience high wind chill, which is defined as exceeding 2000 W $m^{-2}$ (Dery and Yau 1999).

The dynamic tissue-cooling model is not restricted to any particular body site, and it takes into account the thermal and anatomical properties of the site of interest. We applied the model specifically for predictions of cheek cooling for conformity with the development of the WCT, and these predictions compared favorably with several reported observations (Tikuisis and Osczevski 2002). For example, Siple and Passel (1945) reported a cheek freezing time of about 6 min of one individual exposed to a temperature of -32.5°C and a 7 m $s^{-1}$ wind. This condition pertains to the previously defined wind chill index (WCI) of 2272 W $m^{-2}$ and to the new WCT of -48°C (-54°F). We obtained a similar freezing time using the dynamic model under the assumption that freezing occurs at a tissue temperature of -4.8°C (Danielsson 1996). Under a more severe wind such as 25 m $s^{-1}$, corresponding to a WCI of 2694 W $m^{-2}$ and a WCT of -57°C (-71°F), cheek freezing is predicted to occur at around 2 min or less, if a higher than average cheek thermal resistance is assumed. This prediction also concurs with the observations of Siple and Passel (1945).

Below, we apply the dynamic model for the prediction of cheek freezing times forcombinations of air temperature and wind speed extracted from the WCT chart. Cheek characteristics are adopted from Table 1 of Tikuisis and Osczevski (2002), most notably a cheek

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The dynamic tissue-cooling model is not restricted to any particular body site, and it takes into account the thermal and anatomical properties of the site of interest. We applied the model specifically for predictions of cheek cooling for conformity with the development of the WCT, and these predictions compared favorably with several reported observations (Tikuisis and Osczevski 2002). For example, Siple and Passel (1945) reported a cheek freezing time of about 6 min of one individual exposed to a temperature of −32.5°C and a 7 m $s^{-1}$ wind. This condition pertains to the previously defined wind chill index (WCI) of 2272 W $m^{-2}$ and to the new WCT of −48°C (−54°F). We obtained a similar freezing time using the dynamic model under the assumption that freezing occurs at a tissue temperature of −4.8°C (Danielsson 1996). Under a more severe wind such as 25 m $s^{-1}$, corresponding to a WCI of 2694 W $m^{-2}$ and a WCT of −57°C (−71°F), cheek freezing is predicted to occur at around 2 min or less, if a higher than average cheek thermal resistance is assumed. This prediction also concurs with the observations of Siple and Passel (1945).

Below, we apply the dynamic model for the prediction of cheek freezing times forcombinations of air temperature and wind speed extracted from the WCT chart. Cheek characteristics are adopted from Table 1 of Tikuisis and Osczevski (2002), most notably a cheek

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thickness of 12 mm and a cheek thermal resistance of 0.05 $m^2$ K $W^{-1}$. The assumption that the latter value (pertaining to the average individual) is constant as the cheek cools is reasonable because the emphasis in this study is on the time to the onset of freezing; any change in thermal resistance due to freezing would only affect the late cooling period.

**MODEL APPLICATION.** Upon exposure to cold, the unprotected skin will experience a sudden drop in temperature followed by an asymptotic approach to a steady-state value, as demonstrated in Fig. 1 (also see Tikuisis and Osczevski 2002). Steady-state cheek temperatures ($T_{ss}$) are practically reached within 30 min of exposure. Table 1 confirms that shorter times to freezing are predicted as air temperature ($T_a$) decreases and wind speed ($v$) increases. Wind speed at the face level is, at most, of that measured 10 m off the ground, at the height of a standard anemometer (Osczevski 1995). The shaded regions in Table 1 indicate when the cheek temperature ($T_s$) reaches −4.8°C, adopted herein as the onset of freezing (Danielsson 1996). In addition, the predicted rate of cooling is faster for certain combinations of $T_a$ and $v$ that result in the same $T_{ss}$. For example, $T_{ss}$ = −16.8°C for exposures to −42.5°C and 20 km $h^{-1}$, and −30°C and an 80 km $h^{-1}$ facial wind, yet the time to freezing is longer (almost by a factor of 2) for the former condition, as shown in Fig. 1. Other examples are indicated in bold in Table 1.

Table 2 shows the conditions for which cheek skin temperature is predicted to reach 10°C. We purposely chose this value because it approximates when the cheeks feel quite painful (Osczevski 1995) and, thus, it represents an important threshold for predicting a behavioral response to the cold exposure. Again note the asymmetrical relationship where cooling times to 10°C are faster at higher wind speeds for various combinations of $T_a$ and $v$ that result in the same $T_{ss}$ (several examples are indicated in bold). In particular, the combinations of −32.5°C and 10 km $h^{-1}$, −20°C and 40 km $h^{-1}$, and −15°C and 100 km $h^{-1}$ facial winds all result in the same $T_{ss}$ of −5.9°C, yet the times to 10°C are 164, 90, and 53 s, respectively.

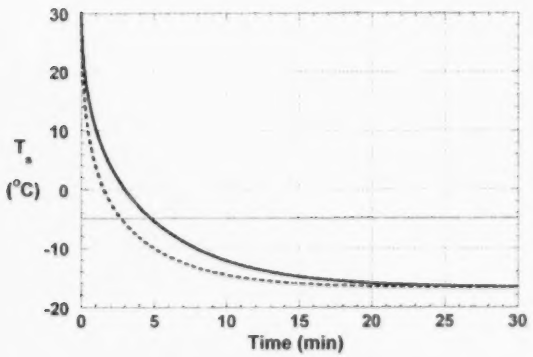


**FIG. 1. Predicted cheek skin temperature ($T_s$) for exposures to −42.5°C and 20 km $h^{-1}$ (thick solid line), and −30°C and an 80 km $h^{-1}$ (thick dashed line) facial wind. The cheek surface is predicted to reach 10°C in 1.0 and 0.5 min, respectively, to freeze (threshold indicated by the thin solid line) in 4.7 and 2.7 min, and to reach a final steady state temperature ($T_{ss}$) of −16.8°C.**

In Table 3, the superposition of the cooling times to freezing onto the new WCT values demonstrate the same asymmetry that was noted in Tables 1 and 2, in this case for various combinations of $T_a$ and $v$ that result in the same WCT. The WCT values (°C) were obtained from (additional information found online at www.msc.ec.gc.ca/education/windchill/Science_equations_e.cfm):

$$\mathrm{WCT} = 13.12 + 0.6215T_a - 11.37v_{10}^{0.16} + 0.3965T_a v_{10}^{0.16}, \quad (1)$$

where $v_{10}$ is the wind speed (km $h^{-1}$) at 10 m above the ground. Two examples are particularly striking (shown in bold), the first involving combinations of −45°C and 5 km $h^{-1}$, and −35°C and 35 km $h^{-1}$ wind that result in a common WCT of −53°C, yet the predicted risk of freezing is less than 5% for the former case and freezing is predicted to occur at 6 min in the latter case. Further, the respective predicted steady-state cheek temperatures are −4.0 and −13.1°C. In the other example, combinations of −50°C and 10 km $h^{-1}$, and −40°C and 50 km $h^{-1}$ wind lead to a WCT of −63°C, but with predicted onsets of freezing at 9.3 and 3.4 min, and $T_{ss}$ values of −12.0° and −18.9°C, respectively. These examples demonstrate that similar values of WCT should not be associated with the same risk of cold injury. Instead, the WCT is based on the steady-state rate of heat loss, which can be the same for different steady-state cheek temperatures under different combinations of $T_a$ and $v$. Although not shown, cooling times are also shorter for the higher wind condition for similar values of WCI.

**DISCUSSION.** The asymmetrical cooling times can be explained by the greater cooling effect of increasing wind as compared to decreasing air temperature for various combinations of $T_a$ and $v$ that result in the same steady-state cheek temperature, and are, therefore, equivalent in terms of cold strain or the potential to inflict cold injury. The exposure-dependent

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**Table 1. Wind chill charts (SI and British units) showing steady-state skin temperatures ($T_{ss}$) and predicted times to freezing (shaded regions; see legend below) of an exposed cheek. Wind values are shown for 10 m off the ground and at face level (see text for an explanation of the bold values of $T_{ss}$).**

| Wind (km h$^{-1}$) | | Air temperature (°C) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 m | Face | −10.0 | −12.5 | −15.0 | −17.5 | −20.0 | −22.5 | −25.0 | −27.5 | −30.0 | −32.5 | −35.0 | −37.5 | −40.0 | −42.5 | −45.0 |
| 15 | 10 | 6.9 | 5.5 | 4.0 | 2.6 | 1.2 | −0.2 | −1.6 | −3.1 | −4.5 | −5.9 | −7.2 | −8.6 | −10.0 | −11.4 | −12.8 |
| 30 | 20 | 4.0 | 2.4 | 0.8 | −0.9 | −2.5 | −4.1 | −5.7 | −7.3 | −8.9 | −10.5 | −12.1 | −13.7 | −15.2 | −16.8 | −18.4 |
| 45 | 30 | 2.4 | 0.6 | −1.1 | −2.8 | −4.5 | −6.2 | −7.9 | −9.7 | −11.4 | −13.1 | −14.8 | −16.5 | −18.2 | −19.9 | −21.6 |
| 60 | 40 | 1.3 | −0.5 | −2.3 | −4.1 | −5.9 | −7.7 | −9.5 | −11.3 | −13.0 | −14.8 | −16.6 | −18.4 | −20.2 | −21.9 | −23.7 |
| 75 | 50 | 0.4 | −1.4 | −3.3 | −5.1 | −6.9 | −8.8 | −10.6 | −12.5 | −14.3 | −16.1 | −18.0 | −19.8 | −21.6 | −23.4 | |
| 90 | 60 | −0.2 | −2.1 | −4.0 | −5.9 | −7.8 | −9.6 | −11.5 | −13.4 | −15.3 | −17.2 | −19.0 | −20.9 | | | |
| 105 | 70 | −0.7 | −2.7 | −4.6 | −6.5 | −8.4 | −10.3 | −12.3 | −14.2 | −16.1 | −18.0 | −19.9 | | | | |
| 120 | 80 | −1.2 | −3.1 | −5.1 | −7.0 | −9.0 | −10.9 | −12.9 | −14.8 | −16.8 | −18.7 | | | | | |
| 135 | 90 | −1.6 | −3.5 | −5.5 | −7.5 | −9.5 | −11.4 | −13.4 | −15.4 | −17.3 | −19.3 | | | | | |
| 150 | 100 | −1.9 | −3.9 | −5.9 | −7.9 | −9.9 | −11.9 | −13.9 | −15.8 | −17.8 | | | | | | |

| Wind (mph) | | Air temperature (°F) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 m | Face | 20.0 | 15.0 | 10.0 | 5.0 | 0.0 | −5.0 | −10.0 | −15.0 | −20.0 | −25.0 | −30.0 | −35.0 | −40.0 | −45.0 |
| 7.5 | 5 | 49.4 | 46.6 | 43.9 | 41.1 | 38.4 | 35.7 | 33.0 | 30.3 | 27.6 | 25.0 | 22.3 | 19.6 | 17.0 | 14.4 |
| 15 | 10 | 44.6 | 41.5 | 38.3 | 35.2 | 32.1 | 29.0 | 25.9 | 22.9 | 19.8 | 16.7 | 13.6 | 10.6 | 7.5 | 4.5 |
| 22.5 | 15 | 41.9 | 38.5 | 35.2 | 31.9 | 28.5 | 25.2 | 21.9 | 18.6 | 15.3 | 12.0 | 8.7 | 5.4 | 2.2 | −1.1 |
| 30 | 20 | 40.0 | 36.5 | 33.0 | 29.5 | 26.1 | 22.6 | 19.1 | 15.7 | 12.2 | 8.8 | 5.3 | 1.9 | | |
| 37.5 | 25 | 38.6 | 35.0 | 31.4 | 27.8 | 24.2 | 20.6 | 17.1 | 13.5 | 9.9 | 6.4 | 2.8 | | | |
| 45 | 30 | 37.5 | 33.8 | 30.1 | 26.4 | 22.8 | 19.1 | 15.4 | 11.8 | 8.1 | | | | | |
| 52.5 | 35 | 36.6 | 32.8 | 29.1 | 25.3 | 21.6 | 17.8 | 14.1 | 10.4 | | | | | | |
| 60 | 40 | 35.8 | 32.0 | 28.2 | 24.4 | 20.6 | 16.8 | 13.0 | 9.2 | | | | | | |
| 67.5 | 45 | 35.1 | 31.3 | 27.4 | 23.6 | 19.7 | 15.9 | 12.0 | | | | | | | |
| 75 | 50 | 34.6 | 30.7 | 26.8 | 22.9 | 19.0 | 15.1 | 11.2 | | | | | | | |
| 82.5 | 55 | 34.1 | 30.1 | 26.2 | 22.2 | 18.3 | 14.4 | 10.4 | | | | | | | |
| 90 | 60 | 33.6 | 29.6 | 25.6 | 21.7 | 17.7 | 13.7 | | | | | | | | |

< 5% risk at any time
> 8 min
Between 4 and 8 min
Between 2 and 4 min
< 2 min

factor (i.e., subject to changes in $T_a$ and $v$) that governs the initial rate of skin cooling is the product of the convective heat transfer coefficient ($h_c$) and the temperature difference between the air and skin. Under the above constraint that the combination of $T_a$ and $v$ yields a common $T_{ss}$, this rate-limiting factor is reduced to the product of $h_c$ and $(T_{ss} - T_s)$ (see appendix for derivation). Because the latter term is initially fixed and $h_c$ is proportional to approximately the square root of the wind speed on the face (Tikuisis and Osczevski 2002), it follows that the initial rate of decrease in $T_s$ increases nonlinearly with increasing $v$. This occurs despite a smaller temperature difference between the air and skin, as a consequence of the constraint that $T_a$ must increase to maintain a common $T_{ss}$. The example shown in Fig. 1 demonstrates this relationship. Further, the nature of this relationship is invariant to the presence of solar radiation, which would cause $T_{ss}$ to increase and the cooling rate to decrease for all combinations of $T_a$ and $v$.

TABLE 1. Wind chill charts (SI and British units) showing steady-state skin temperatures ($T_{ss}$) and predicted times to freezing (shaded regions; see legend below) of an exposed cheek. Wind values are shown for 10 m off the ground and at face level (see text for an explanation of the bold values of $T_{ss}$).

| Wind (km h$^{-1}$) | | Air temperature (°C) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 m | Face | −10.0 | −12.5 | −15.0 | −17.5 | −20.0 | −22.5 | −25.0 | −27.5 | −30.0 | −32.5 | −35.0 | −37.5 | −40.0 | −42.5 | −45.0 |
| 15 | 10 | 6.9 | 5.5 | 4.0 | 2.6 | 1.2 | −0.2 | −1.6 | −3.1 | −4.5 | −5.9 | −7.2 | −8.6 | −10.0 | −11.4 | −12.8 |
| 30 | 20 | 4.0 | 2.4 | 0.8 | −0.9 | −2.5 | −4.1 | −5.7 | −7.3 | −8.9 | −10.5 | −12.1 | −13.7 | −15.2 | −16.8 | −18.4 |
| 45 | 30 | 2.4 | 0.6 | −1.1 | −2.9 | −4.8 | −6.2 | −7.9 | −9.7 | −11.4 | −13.1 | −14.8 | −16.5 | −18.2 | −19.9 | −21.6 |
| 60 | 40 | 1.3 | −0.5 | −2.3 | −4.1 | −5.9 | −7.7 | −9.5 | −11.3 | −13.0 | **−14.8** | −16.6 | −18.4 | −20.2 | −21.9 | **−23.7** |
| 75 | 50 | 0.4 | −1.4 | −3.3 | −5.1 | −6.9 | −8.8 | −10.6 | −12.5 | −14.3 | −16.1 | −18.0 | **−19.8** | −21.6 | −23.4 | −25.3 |
| 90 | 60 | −0.2 | −2.1 | −4.0 | −5.9 | −7.8 | −9.6 | −11.5 | −13.4 | −15.3 | −17.2 | −19.0 | −20.9 | **−22.8** | −24.6 | −26.5 |
| 105 | 70 | −0.9 | −2.7 | −4.6 | −6.5 | −8.4 | −10.3 | −12.3 | −14.2 | −16.1 | −18.0 | −19.9 | −21.8 | **−23.7** | −25.6 | −27.5 |
| 120 | 80 | −1.3 | −3.1 | −5.1 | −7.0 | −9.0 | −10.9 | −12.9 | **−14.8** | −16.8 | −18.7 | **−20.6** | −22.6 | −24.5 | −26.4 | −28.4 |
| 135 | 90 | −1.8 | −3.6 | −5.5 | −7.5 | −9.5 | −11.4 | −13.4 | −15.4 | −17.3 | −19.3 | −21.3 | −23.2 | −25.2 | −27.1 | −29.1 |
| 150 | 100 | −1.9 | −3.9 | −5.9 | **−7.9** | −9.9 | −11.9 | −13.9 | −15.8 | −17.8 | **−19.8** | −21.8 | −23.8 | −25.8 | −27.7 | −29.7 |

| Wind (mph) | | Air temperature (°F) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 m | Face | 20.0 | 15.0 | 10.0 | 5.0 | 0.0 | −5.0 | −10.0 | −15.0 | −20.0 | −25.0 | −30.0 | −35.0 | −40.0 | −45.0 |
| 7.5 | 5 | 49.4 | 46.6 | 43.9 | 41.1 | 38.4 | 35.6 | 32.9 | 30.1 | 27.4 | 24.6 | 22.3 | 19.6 | 17.0 | 14.4 |
| 15 | 10 | 44.6 | 41.5 | 38.3 | 35.2 | 32.1 | 29.0 | 25.9 | 22.9 | 19.8 | 16.7 | 13.6 | 10.6 | 7.5 | 4.5 |
| 22.5 | 15 | 41.8 | 38.8 | 35.2 | 31.9 | 28.5 | 25.2 | 21.9 | 18.6 | 15.3 | 12.0 | 8.7 | 5.4 | 2.2 | −1.1 |
| 30 | 20 | 40.1 | 36.8 | 33.5 | 29.8 | 26.2 | 22.6 | 19.1 | 15.7 | 12.2 | 8.8 | 5.3 | 1.9 | −1.5 | −4.9 |
| 37.5 | 25 | 38.8 | 35.0 | 31.4 | 27.8 | 24.2 | 20.6 | 17.1 | 13.5 | 9.9 | 6.4 | 2.8 | −0.7 | −4.3 | −7.8 |
| 45 | 30 | 37.8 | 33.8 | 30.1 | 26.4 | 22.8 | 19.1 | 15.4 | 11.8 | 8.1 | 4.5 | 0.8 | −2.8 | −6.4 | −10.1 |
| 52.5 | 35 | 36.9 | 32.8 | 29 | 25.3 | 21.6 | 17.8 | 14.1 | 10.4 | 6.6 | 2.9 | −0.8 | −4.5 | −8.2 | −11.9 |
| 60 | 40 | 35.8 | 32.0 | 28.2 | 24.4 | 20.6 | 16.8 | 13.0 | 9.2 | 5.4 | 1.6 | −2.2 | −5.9 | −9.7 | −13.5 |
| 67.5 | 45 | 35.1 | 31.3 | 27.4 | 23.6 | 19.7 | 15.9 | 12.0 | 8.2 | 4.3 | 0.5 | −3.3 | −7.2 | −11.0 | −14.8 |
| 75 | 50 | 34.6 | 30.7 | 26.8 | 22.9 | 19.0 | 15.1 | 11.2 | 7.3 | 3.4 | −0.5 | −4.4 | −8.2 | −12.1 | −16.0 |
| 82.5 | 55 | 34.1 | 30 | 26.2 | 22.2 | 18.3 | 14.4 | 10.4 | 6.5 | 2.6 | −1.3 | −5.3 | −9.2 | −13.1 | −17.0 |
| 90 | 60 | 33.6 | 29.6 | 25.8 | 21.7 | 17.7 | 13.7 | 9.8 | 5.8 | 1.8 | −2.1 | −6.1 | −10.0 | −14.0 | −17.9 |

< 5% risk at any time

> 8 min

Between 4 and 8 min

Between 2 and 4 min

< 2 min

Table 2. Wind chill chart (SI units) showing steady-state facial temperatures (°C) and predicted times to reach temperatures of 10°C (underlined values) and 0°C (bold values) for an exposed cheek. Wind speeds are shown for 10 m (2 m wind speeds are 67% of the values shown) and at face level (see text for explanation of the bold values).

| Wind (km h⁻¹) | | Air temperature (°C) | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 m | Face | 5.0 | 2.5 | 0.0 | −2.5 | −5.0 | −7.5 | −10.0 | −12.5 | −15.0 | −17.5 | −20.0 | −22.5 | −25.0 | −27.5 | −30.0 | −32.5 | −35.0 | −37.5 | −40.0 | −42.5 | −45.0 |
| 15 | 10 | 15.6 | 14.1 | 12.7 | 11.2 | 9.8 | 8.3 | 6.9 | 5.5 | 4.0 | 2.6 | 1.2 | −0.2 | −1.6 | −3.1 | −4.5 | −5.9 | −7.4 | −8.8 | −10.2 | −11.7 | −13.1 |
| 30 | 20 | 13.8 | 12.2 | 10.5 | 8.9 | 7.2 | 5.6 | 4.0 | 2.4 | 0.8 | −0.9 | −2.5 | −4.1 | −5.7 | −7.3 | −8.9 | −10.5 | −12.1 | −13.7 | −15.3 | −16.9 | −18.5 |
| 45 | 30 | 12.8 | 11.0 | 9.3 | 7.6 | 5.8 | 4.1 | 2.3 | 0.6 | −1.1 | −2.8 | −4.5 | −6.2 | −7.9 | −9.6 | −11.3 | −13.1 | −14.8 | −16.5 | −18.2 | −19.9 | −21.6 |
| 60 | 40 | 12.1 | 10.3 | 8.5 | 6.7 | 4.9 | 3.1 | 1.3 | −0.5 | −2.3 | −4.1 | −5.9 | −7.7 | −9.5 | −11.3 | −13.1 | −14.9 | −16.7 | −18.5 | −20.3 | −22.1 | −23.9 |
| 75 | 50 | 11.6 | 9.7 | 7.9 | 6.0 | 4.1 | 2.1 | 0.2 | −1.7 | −3.6 | −5.5 | −7.4 | −9.3 | −11.2 | −13.1 | −15.0 | −16.9 | −18.8 | −20.7 | −22.6 | −24.5 | −26.4 |
| 90 | 60 | 11.2 | 9.3 | 7.4 | 5.5 | 3.6 | 1.7 | −0.2 | −2.1 | −4.0 | −5.9 | −7.8 | −9.7 | −11.6 | −13.5 | −15.4 | −17.3 | −19.2 | −21.1 | −23.0 | −24.9 | −26.8 |
| 105 | 70 | 10.9 | 8.9 | 7.0 | 5.0 | 3.1 | 1.2 | −0.8 | −2.7 | −4.6 | −6.5 | −8.4 | −10.3 | −12.2 | −14.2 | −16.1 | −18.0 | −19.9 | −21.8 | −23.7 | −25.6 | −27.5 |
| 120 | 80 | 10.6 | 8.6 | 6.6 | 4.7 | 2.7 | 0.8 | −1.1 | −3.0 | −4.9 | −6.8 | −8.8 | −10.7 | −12.6 | −14.5 | −16.4 | −18.3 | −20.2 | −22.1 | −24.0 | −25.9 | −27.8 |
| 135 | 90 | 10.3 | 8.3 | 6.4 | 4.4 | 2.4 | 0.5 | −1.5 | −3.4 | −5.3 | −7.2 | −9.1 | −11.0 | −13.0 | −14.9 | −16.8 | −18.7 | −20.6 | −22.5 | −24.4 | −26.3 | −28.2 |
| 150 | 100 | 10.1 | 8.1 | 6.1 | 4.1 | 2.1 | 0.2 | −1.8 | −3.7 | −5.6 | −7.5 | −9.5 | −11.4 | −13.3 | −15.2 | −17.1 | −19.0 | −20.9 | −22.8 | −24.7 | −26.6 | −28.5 |

not reached
> 8 min
Between 4 and 8 min
Between 2 and 4 min
between 1 and 2 min
< 1 min

This finding suggests that a windier condition might be initially perceived to be more stressful than less wind at a lower temperature that results in the same final steady-state cheek temperature or WCT. Indeed, Burton and Edholm (1955) noted that increased cold sensation, mainly from the face, should elicit a strong vasomotor response to mitigate overall heat loss by reducing blood circulation to the extremities, resulting in colder hands and feet. Thus, complaints of cold might be more common in mild but windy climates than in cold climates with less wind when the wind chill is the same. This might partly explain why many people perceive the winters in "wet cold" regions as cold or colder than those in "dry cold" regions where the actual air temperatures may be much lower. For a given wind chill, these results also suggest that windier conditions likely expedite any debilitating effect that cold facial skin might present. Thus, any degradation in performance due to cold skin cannot be confidently predicted by knowing only the WCT.

How does humidity factor into the above findings? From a theoretical perspective, the equations that govern convective and radiative heat losses (Tikuisis and Osczevski 2002) are not sensitive to humidity, and, therefore, changes in the cooling rate of skin and its steady-state temperature should be minimally affected, in concurrence with the analysis of Quayle and Steadman (1998). Indeed, Burton et al. (1955) reported that skin temperatures and heat losses were independent of humidity for unclothed subjects at rest when exposed to combinations of air temperatures of 8.9° and 14.4°C, and relative humidities (RH) of 30% and 80%. A similar finding was reported by Iampietro and Buskirk (1960) who exposed lightly clothed individuals to combinations of 4.4° and 10°C, 30% and 100% RH, and wind speeds of 16 and less than 1.6 km $h^{-1}$.

TABLE 1. Wind chill chart (SI units) showing WCT (°C) (see text for an explanation of the bold values) and predicted times to freezing (shaded regions; see legend below) of an exposed cheek. Wind values are shown for 10 m above the ground.

| Wind (km h$^{-1}$) | Air temperature (°C) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $v_{10}$ | 5 | 0 | −5 | −10 | −15 | −20 | −25 | −30 | −35 | −40 | −45 | −50 |
| 5 | 4 | −2 | −7 | −13 | −19 | −24 | −30 | −36 | −41 | −47 | −53 | −58 |
| 10 | 3 | −3 | −9 | −15 | −21 | −27 | −33 | −39 | −45 | −51 | −57 | −63 |
| 15 | 2 | −4 | −11 | −17 | −23 | −29 | −35 | −41 | −48 | −54 | −60 | −66 |
| 20 | 1 | −5 | −12 | −18 | −24 | −30 | −37 | −43 | −49 | −56 | −62 | −69 |
| 25 | 1 | −6 | −12 | −19 | −25 | −32 | −38 | −44 | −51 | −57 | −64 | −70 |
| 30 | 0 | −6 | −13 | −20 | −26 | −33 | −39 | −46 | −52 | −59 | −65 | −72 |
| 35 | 0 | −7 | −14 | −20 | −27 | −33 | −40 | −47 | −53 | −60 | −66 | −73 |
| 40 | −1 | −7 | −14 | −21 | −27 | −34 | −41 | −48 | −54 | −61 | −68 | −74 |
| 45 | −1 | −8 | −15 | −21 | −28 | −35 | −42 | −48 | −55 | −62 | −69 | −75 |
| 50 | −1 | −8 | −15 | −22 | −29 | −35 | −42 | −49 | −56 | −63 | −69 | −76 |
| 55 | −2 | −8 | −15 | −22 | −29 | −36 | −43 | −50 | −57 | −63 | −70 | −77 |
| 60 | −2 | −9 | −16 | −23 | −30 | −36 | −43 | −50 | −57 | −64 | −71 | −78 |
| 65 | −2 | −9 | −16 | −23 | −30 | −37 | −44 | −51 | −58 | −65 | −72 | −79 |
| 70 | −2 | −9 | −16 | −23 | −30 | −37 | −44 | −51 | −58 | −65 | −72 | −80 |
| 75 | −3 | −10 | −17 | −24 | −31 | −38 | −45 | −52 | −59 | −66 | −73 | −81 |
| 80 | −3 | −10 | −17 | −24 | −31 | −38 | −45 | −52 | −60 | −67 | −74 | −81 |

< 5% risk at any time
> 8 min
Between 4 and 8 min
Between 2 and 4 min
< 2 min

The above results might appear contrary to the anecdotal evidence that increased moisture in the air exacerbates the sensation of cold. While the above experimental comparisons were applied under controlled climatic conditions with no solar radiation, real weather can invoke significant differences in the perception of cold at the same air temperature. Whereas turbulent wind is more prevalent under damp conditions and, therefore, likely to promote heat loss, solar radiation is more prevalent under drier conditions and likely to contribute to a lesser sensation of cold (Renbourne 1972).

For any individual, a higher wind speed or lower air temperature means a higher rate of facial heat loss and a more severe WCT. For a number of individuals at the same $T_a$ and $v$, but having a range of cheek thermal resistances, the individual with the lowest cheek thermal resistance would have the highest rate of facial heat loss. A WCT calculated for this individual, based on facial heat loss, would, therefore, be the most severe of the group; yet that individual would also have the highest facial skin temperature, would feel the warmest, and be the least likely to suffer cold injury. That the least uncomfortable and least susceptible individual should have the most severe WCT is counterintuitive, but this is the correct interpretation of the WCT. The proposed prediction of times to critical facial temperatures using the dynamic tissue-cooling model avoids this paradoxical result. In the same group, the individual with the lowest cheek thermal resistance, who should be the least affected by the weather, would be predicted to have the longest cooling time to a critical facial temperature and the highest final (steady state) cheek temperature.

In addition to the different interpretations between the WCT and wind chill estimates of the dynamic tissue cooling model, there are important differences in the assumptions that were applied in the construction of these models. In the former case, a

TABLE 2. Wind chill chart (SI units) showing steady-state skin temperatures ($T_{ss}$) and predicted times to a temperature of 10 °C (shaded regions; see legend below) of an exposed cheek. Wind values are shown for 10 m off the ground and at face level (see text for explanation of the bold values of $T_{ss}$).

| Wind (km h⁻¹) | | Air temperature (°C) | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 m | Face | 5.0 | 2.5 | 0.0 | −2.5 | −5.0 | −7.5 | −10.0 | −12.5 | −15.0 | −17.5 | −20.0 | −22.5 | −25.0 | −27.5 | −30.0 | −32.5 | −35.0 | −37.5 | −40.0 | −42.5 | −45.0 |
| 15 | 10 | 15.6 | 14.1 | 12.7 | 11.3 | 9.8 | 8.3 | 6.9 | 5.5 | 4.0 | 2.6 | 1.2 | −0.2 | −1.6 | −3.1 | −4.5 | **−5.9** | −7.2 | −8.6 | −10.0 | −11.4 | −12.8 |
| 30 | 20 | 14.8 | 13.3 | 10.5 | 8.9 | 7.2 | 5.6 | 4.0 | 2.4 | 0.8 | −0.9 | −2.5 | −4.1 | −5.7 | −7.3 | −8.9 | −10.5 | −12.1 | −13.7 | −15.2 | **−16.8** | −18.4 |
| 45 | 30 | 13.8 | 11.0 | 9.3 | 7.6 | 5.8 | 4.1 | 2.4 | 0.6 | −1.1 | −2.8 | −4.5 | −6.2 | −7.9 | −9.7 | −11.4 | −13.1 | −14.8 | −16.5 | −18.2 | −19.9 | −21.6 |
| 60 | 40 | 12.1 | 10.3 | 8.5 | 6.7 | 4.9 | 3.1 | 1.3 | −0.5 | −2.3 | −4.1 | **−5.9** | −7.7 | −9.5 | −11.3 | −13.0 | −14.8 | −16.6 | −18.4 | −20.2 | −21.9 | −23.7 |
| 75 | 50 | 11.6 | 9.7 | 7.9 | 6.0 | 4.1 | 2.3 | 0.4 | −1.4 | −3.3 | −5.1 | −6.9 | −8.8 | −10.6 | −12.5 | −14.3 | −16.1 | −18.0 | −19.8 | −21.6 | −23.4 | −25.3 |
| 90 | 60 | 11.2 | 9.3 | 7.4 | 5.5 | 3.6 | 1.7 | −0.2 | −2.1 | −4.0 | −5.9 | −7.8 | −9.6 | −11.5 | −13.4 | −15.3 | −17.2 | −19.0 | −20.9 | −22.8 | −24.6 | −26.5 |
| 105 | 70 | 10.9 | 8.9 | 7.0 | 5.0 | 3.1 | 1.2 | −0.7 | −2.7 | −4.6 | −6.5 | −8.4 | −10.3 | −12.3 | −14.2 | −16.1 | −18.0 | −19.9 | −21.8 | −23.7 | −25.6 | −27.5 |
| 120 | 80 | 10.6 | 8.6 | 6.6 | 4.7 | 2.7 | 0.8 | −1.2 | −3.1 | −5.1 | −7.0 | −9.0 | −10.9 | −12.9 | −14.8 | −16.8 | −18.7 | −20.6 | −22.6 | −24.5 | −26.4 | −28.4 |
| 135 | 90 | 10.3 | 8.3 | 6.4 | 4.4 | 2.4 | 0.4 | −1.6 | −3.5 | −5.5 | −7.5 | −9.5 | −11.5 | −13.4 | −15.4 | −17.3 | −19.3 | −21.3 | −23.2 | −25.2 | −27.1 | −29.1 |
| 150 | 100 | 10.1 | 8.1 | 6.1 | 4.1 | 2.1 | 0.1 | −1.9 | −3.9 | −5.9 | −7.9 | −9.9 | −11.9 | −13.8 | −15.8 | −17.8 | −19.8 | −21.8 | −23.8 | −25.8 | −27.7 | −29.7 |

not reached
> 8 min

Between 4 and 8 min

Between 2 and 4 min

between 1 and 2 min

< 1 min

**Table 3. Wind chill chart (SI units) showing WCT (°C) (see text for an explanation of the bold values) and predicted times to freezing (shaded regions; see legend below) of an exposed cheek. Wind values are shown for 10 m above the ground.**

| Wind (km h$^{-1}$) | Air temperature (°C) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $v_{10}$ | 5 | 0 | −5 | −10 | −15 | −20 | −25 | −30 | −35 | −40 | −45 | −50 |
| 5 | 4 | 2 | −3 | −9 | −11 | −16 | −22 | −28 | −34 | −40 | −47 | −53 | −58 |
| 10 | 3 | −3 | −9 | −15 | −21 | −27 | −33 | −39 | −45 | −51 | −57 | −63 |
| 15 | 2 | −4 | −11 | −17 | −23 | −29 | −35 | −41 | −48 | −54 | −60 | −66 |
| 20 | 1 | −5 | −12 | −18 | −24 | −30 | −37 | −43 | −49 | −56 | −62 | −68 |
| 25 | 1 | −6 | −13 | −19 | −25 | −32 | −38 | −44 | −51 | −57 | −64 | −70 |
| 30 | 0 | −6 | −13 | −20 | −26 | −33 | −39 | −46 | −52 | −59 | −65 | −72 |
| 35 | 0 | −7 | −14 | −20 | −27 | −33 | −40 | −47 | −53 | −60 | −66 | −73 |
| 40 | 0 | −7 | −14 | −21 | −27 | −34 | −41 | −48 | −54 | −61 | −68 | −74 |
| 45 | −1 | −8 | −15 | −21 | −28 | −35 | −42 | −48 | −55 | −62 | −69 | −75 |
| 50 | −1 | −8 | −15 | −22 | −29 | −35 | −42 | −49 | −56 | −63 | −69 | −76 |
| 55 | −1 | −8 | −15 | −22 | −29 | −36 | −42 | −50 | −57 | −63 | −70 | −77 |
| 60 | −1 | −8 | −16 | −22 | −30 | −36 | −43 | −50 | −57 | −64 | −71 | −78 |
| 65 | −1 | −9 | −16 | −23 | −30 | −37 | −44 | −51 | −58 | −65 | −72 | −79 |
| 70 | −1 | −9 | −16 | −23 | −30 | −37 | −44 | −51 | −58 | −65 | −72 | −80 |
| 75 | −1 | −10 | −17 | −24 | −31 | −38 | −45 | −52 | −59 | −66 | −73 | −80 |
| 80 | −1 | −10 | −17 | −24 | −31 | −38 | −45 | −52 | −60 | −67 | −74 | −81 |

> 5% risk at any time | Between 4 and 8 min | < 2 min
> 8 min | Between 2 and 4 min

thermal resistance of 0.09 $m^2$ K $W^{-1}$ was applied from the body's core to the skin, in contrast to the lower value of 0.05 $m^2$ K $W^{-1}$ applied across the thickness of the cheek in the dynamic model. The higher resistance used in the WCT approximates the most susceptible 5% of the general population. The lower resistance used in the dynamic model is more representative of the average individual. Also, a high core temperature of 38°C was assumed for the WCT model based on a walking exposure to cold, in contrast to an interior cheek temperature of 34°C assumed in the dynamic model. The assumptions used in the dynamic model were validated with observational and experimental data that largely included stationary individuals (Tikuisis and Osczevski 2002). These model differences indicate that the new WCT index should be considered conservative while the predictions of the dynamic model presented herein are applicable to the average individual facing the wind in a stationary posture.

**CONCLUDING REMARKS.** The WCT is the calm air equivalent that results in the same rate of steady-state heat loss as an exposure to a higher temperature with wind. The dynamic tissue-cooling model, on the other hand, provides a prediction of the nonsteady-state rate of cooling thereby allowing determinations of not only if, but when the risk of freezing occurs. This distinction becomes even more important under conditions where cooling rates are different for similar resultant values of the steady-state cheek temperature or wind chill. That is, given different combinations of air temperature and wind speed that lead to the same $T_{ss}$ or WCT, facial cooling will be faster in the higher wind condition. Should freezing occur, the risk is correspondingly advanced, as shown in Fig. 1 and Tables 1 and 3.

We believe that the prediction of times to critical facial temperatures (or safe exposure limits) is more meaningful and easier to interpret than the WCT. This view was also strongly endorsed by Brauner and Shacham (1995). In place of substitute temperatures (i.e., WCT) to describe a cold wind condition, cooling times would provide an unambiguous direct measure of the risk of cold injury. Cooling times or safe exposure limits also provide an obvious advantage for planning purposes, knowing at what point protection from the cold is required. Further, the dynamic model can be applied to individual thermal and anatomical features for greater specificity. Guidance on cooling times are available with the WCT (online at www.msc.ec.gc.ca/education/windchill/Windchill_chart_e.cfm), but these are approximate and do not factor in the asymmetry due to increasing wind, as disclosed by the dynamic tissue-cooling model (see Table 3). Although other charts (e.g., see information online at www.nws.noaa.gov/om/windchill/ and www.msc.ec.gc.ca/education/windchill/Minutes_freeze_table_e.cfm) do indicate the asymmetry in cooling times to freezing, these times are estimated.

Tables 1 and 2 pertain to the average individual; cooling times will be shorter with a more susceptible population. For example, by increasing the value of the thermal resistance of the cheek from 0.05 to 0.09 $m^2$ K $W^{-1}$ in the example shown in Fig. 1, the predicted times to freezing decrease from 4.7 to 2.7 min, and from 2.7 to 1.5 min for the respective exposures of −42.5°C and 20 km $h^{-1}$ and −30°C, and 80 km $h^{-1}$ facial wind. Also, other exposed body sites that are smaller and/or narrower than the cheek (eg., nose, fingers, etc.) are more susceptible to cooling. Providing fuller guidance on the susceptibility of these sites and on subpopulations at greater risk would involve considerable documentation beyond the scope of this report. Its purpose was to disclose the asymmetry in cooling rates not evident in similar wind chill or WCT values, and to suggest safe exposure limits as a more meaningful and less ambiguous reporting of the potential risk of injury due to cold wind, not unlike the UV index for exposure to the sun's ultraviolet rays.

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## APPENDIX: ASYMMETRY IN COOLING RATE.

Derivation of the exposure-dependent factor governing the initial cooling rate of skin temperature ($T_s$) under the constraint that the steady-state value ($T_{ss}$) is constant.

The rate of change of skin temperature can be numerically expressed as (Tikuisis and Osczevski 2002)

$$\frac{\Delta T_s}{\Delta t} = \frac{k}{\rho c}\frac{2}{\Delta r^2}(T_{\Delta r} - T_s) + \frac{2h_c(T_a - T_s)}{\rho c \Delta r}\left(1 + \frac{\Delta r}{2r_s}\right), \quad \text{(A1)}$$

where $t$ is time (s), $k$, $\rho$, and $c$ are the thermal conductivity (W $m^{-1}$ $K^{-1}$), density (kg $m^{-3}$), and specific

heat (J kg$^{-1}$ K$^{-1}$) of the cheek tissue, respectively, $\Delta r$ is the thickness (m) of the skin layer, $T_{\Delta r}$ is the temperature below the skin layer, $r_c$ is the radius (m) of the cheek, $h_c$ is theconvective heat transfer coefficient (W m$^{-2}$ K$^{-1}$), and $T_s$ and $T_a$ are the skin and air temperatures, respectively. The radiant heat loss is ignored, as its contribution to differences in cooling rates for a common $T_{ss}$ is relatively minor for the purpose of this derivation. At the start of the exposure, the first term on the right side of Eq. (A1) is invariant to air temperature and wind speed. Thus, any differences in the initial cooling rate of skin temperature depend on the second term, specifically the component $h_c \times (T_a - T_s)$. Under the constraint that a given combination of $T_a$ and $v$ must result in the same value of $T_{ss}$, we can substitute $T_a$ by the following expression (Tikuisis and Osczevski 2002):

$$T_a = T_{ss} + \frac{T_{ss} - T_c}{R h_c}, \qquad \text{(A2)}$$

where $T_c$ is the interior cheek temperature (i.e., at the inner cheek boundary) and $R$ is the thermal resistance (m$^2$ K W$^{-1}$) of the cheek. Direct substitution of this expression leads to

$$h_c (T_a - T_s) = h_c (T_{ss} - T_s) + \frac{(T_{ss} - T_c)}{R}, \qquad \text{(A3)}$$

where only the first term on the right-hand side is subject to variation with respect to changes in wind speed via $h_c$, and, thus, the initial rate of decrease in $T_s$ increases with increasing wind for a given $T_{ss}$.

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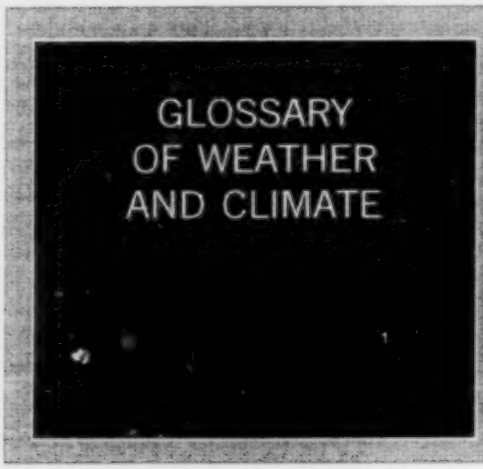


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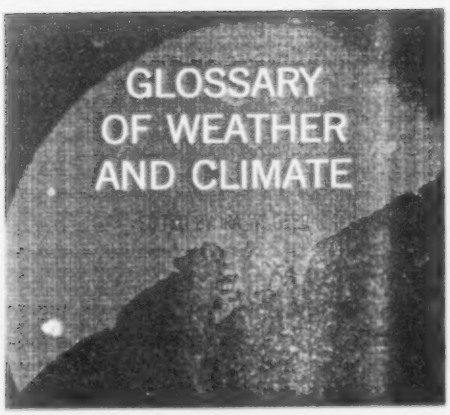


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